MONASH
UNIVERSITY

AUSTRALIA

VOLATILITY PATTERNS AND SPILLOVERS IN BUND FUTURES

Philip Hans Franses, Reinoud van Ieperen,
Paul Kofman, Martin Martens & Bert Menkveld

Working Paper No. 16/94

July 1994

DEPARTMENT OF ECONOMETRICS

ISSN 1032-3813

ISBN 0 7326 0757 4

VOLATILITY PATTERNS AND SPILLOVERS IN BUND FUTURES

Philip Hans Franses, Reinoud van Ieperen,

Paul Kofman, Martin Martens & Bert Menkveld

Working Paper No. 16/94

July 1994

DEPARTMENT OF ECONOMETRICS

MONASH UNIVERSITY, CLAYTON, VICTORIA 3168, AUSTRALIA.

July, 1994

VOLATILITY PATTERNS AND SPILLOVERS IN BUND FUTURES*

Philip Hans Franses(1)

Reinoud van Ieperen(1)

Paul Kofman(2)

Martin Martens(3) and

Bert Menkveld(1)

*This paper emerged from a 'Financial Econometrics'-course given at the Departments of Econometrics and Finance, Erasmus University Rotterdam. We thank all participants in that course for their constructive comments. Financial support from the KNAW (Royal Dutch Academy of Arts and Sciences) and the ECFR (Erasmus Center for Financial Research) is gratefully acknowledged.

(1)Department of Econometrics, Erasmus University Rotterdam, The Netherlands
(2)Department of Econometrics, Monash University, Melbourne, Australia
(3)Department of Finance, Erasmus University Rotterdam, The Netherlands

VOLATILITY PATTERNS AND SPILLOVERS IN BUND FUTURES

ABSTRACT

In this paper we examine intraday volatility of the Bund future, which is traded at the London International Financial Futures Exchange (LIFFE) and the Deutsche Terminbörse (DTB). Our objective is two-fold. First, we investigate spillovers in volatility between the exchanges. Such spillovers are found to occur only within one minute and they do not reveal any systematic lead of one exchange on the other. Second, we study patterns in intraday volatility. Our results indicate that volatility decreases from the opening hour until early afternoon and rises thereafter. The same pattern is detected in explanatory variables like traded volume and time-between-trades. Bid-ask spreads, however, seem to be constant throughout the day.

1. Introduction

The equilibrium price of a particular financial asset, listed at several markets simultaneously, is likely to be determined in all these markets as if it were one asset listed in one market. Even though these different markets often consist of different traders and possibly different trading systems, intraday price series should be almost identical according to no-arbitrage. When the price in one market is higher than the price for the same asset in the other market, an arbitrageur could buy the asset in one market and sell it the same moment in the other market. Hence the arbitrageur can lock in a riskless gain, provided the difference in prices is large enough in comparison with transaction costs.

The similarity of somehow connected price series has been subject of various studies both at the level of returns and at the level of volatility. The interest in volatility interrelatedness seems natural. It is often hard to make predictions about future price movements or returns, see e.g. Granger (1992), while sometimes volatility shows systematic patterns through time and thus can be predicted to some extent. The predictability of volatility can be useful, since it is commonly seen as a measure of risk, and hence may be important in, for example, the pricing of options.

In this paper we investigate the volatility spillovers and patterns of a specific asset, the Bund futures. An important aspect of these futures is that they are only listed at the London International Financial Futures Exchange (LIFFE) and the Deutsche TerminBörse (DTB) in Frankfurt. These two markets have almost the same trading hours. Moreover, our investigation will not be troubled by non-constant exchange rates, since in both markets the price is denoted in percentage points, where one percentage point is 25 DM. For the common trading hours of LIFFE and DTB we investigate whether there are systematic patterns in spillovers of volatility. Such patterns may indicate a lead and/or lag relation in volatility. An interpretation of this phenomenon is that relevant news can originate in one market and disperse eventually to the other market, see e.g. Ederington and Lee (1993) for related results.

Considering the usual strength of arbitrage we expect that differences in pricing, as well as in volatility, do not last very long. This leads us to consider volatility at short intervals. A commonly used measure of volatility is the sample standard deviation or variance of prices or returns. This measure, however, can only be computed for short intervals when there are enough prices or price changes every interval. Given that we are interested in analysing volatility during 1- and 5-minute intervals, we consider the number of price changes as an alternative to sample standard deviation in order to investigate the presence of volatility spillovers between LIFFE and DTB.

Several recent studies have shown a systematic daily pattern in the volatility of liquid assets. Average volatility often is high at the beginning and at the end of a trading-day with low values in between. This U-shape has been detected in equity markets by, e.g., Wood, McInish and Ord (1985) and Lockwood and Linn (1990). Futures markets, however, show rather ambiguous results. Ederington and Lee (1993) do not find such a pattern, while Webb and Smith (1994) detect a U-shape in the volatility of Eurodollar futures. In the present paper, we will investigate the presence of a U-shape pattern for the Bund futures, using the test proposed by Lockwood and Linn (1990). This test can also be applied to intuitively explanatory variables of the volatility process. These proxy variables for information include bid-ask spreads, volume and trading intensity. Studies as Hausman, Lo and MacKinlay (1992), Bollerslev and Domowitz (1993), and Bollerslev and Melvin (1994) suggest that these variables may have explanatory value for volatility. We will also investigate how large the explanatory power of these proxy variables is for the specific pattern in the volatility. Here we specifically relate the U-shape pattern to these proxy variables and we investigate whether these variables can totally explain this pattern.

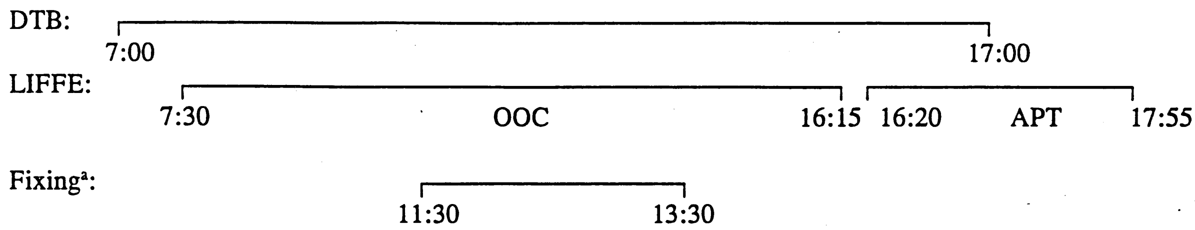
The present paper is organised as follows. The data are presented in Section 2. Section 3 discusses the measures of volatility which we use to detect potential lead/lag relations. This section also contains a description of the test for the daily U-shape pattern in the volatility series as well as in the proxy variables. Section 4 contains the results of our empirical analysis. Concluding remarks are given in Section 5.

2. Data

For this study we use data on the Bund futures contract. The Bund futures contract is an agreement between buyer and seller to exchange a notional 6% German Government Bond (DM 250.000 face value) at a fixed date, for cash with delivery four times a year.

Since September 1988, Bund futures have been traded at the London International Financial Futures Exchange (LIFFE). In November 1990 trading in Bund futures was introduced at the Deutsche TerminBörse (DTB) in Frankfurt. In the considered period, these are the only exchanges on which this contract is traded. We collect our data from London as well as from Frankfurt. Hence, we obtain all relevant data on a financial asset which is traded in a closed system. By this we mean that the price-behaviour is not structurally influenced by external factors like other exchanges. We therefore consider it to be a bivariate system.

LIFFE opens at 7:30 hours, London time (GMT). For convenience we use London time throughout our investigation. Until 16:15 hours trade is organized according to a system of Open Outcry (OOC). After a five-minute break trade is resumed until 17:55 hours using a computerized version of Open Outcry which is called Automated Pit Trading (APT). In Frankfurt, fully automated trading opens at 7:00 hours and closes at 17:00 hours. Our data, however, suggest that trading in Frankfurt stops at 16:30. Official trade in the underlying asset takes place from 11:30 until 13:30 hours which is called the fixing period. A time table is given in Figure 1:



[a]: Time in which the Bund itself is traded

Figure 1: A time scheme of trading on DTB (Frankfurt) and LIFFE (London). Time is measured according to London time (GMT).

Our dataset contains all transactions of 30 trading days in the period from March 2 until April 10, 1992. Time, volume and trading price is known for each transaction. For LIFFE we also have bid- and ask quotes. We do not know all quotes, since the ones that have been hit immediately were recorded as transactions. Therefore, we cannot identify whether transactions were initiated by a buyer or a seller.

One reason to select the aforementioned specific days is that our sample period covers some interesting news facts like the British national elections on April, 9, 1992. For example, rumours on the Labour party replacing the Conservative government may influence the exchanges. Some facts from the daily Financial Times report on the Bund futures are given in Figure 2. We expect that some of these facts may be reflected in our empirical results on volatility spillovers.

Figure 2: Financial news concerning DTB (Frankfurt) and LIFFE (London), 1992, taken from the Financial Times

March 2	Germany's Treuhand agency reports on succesful selling of half of the former East German state companies
March 3	Budget and election worries prompted profit taking behaviour in the UK government bond market
March 4	DTB - rumours on interest cut are disturbed due to Bundesbank's decision to drain DM 2.5bn from the market at yesterday's security (Bund future) repurchase tender
March 5	LIFFE - expiration of March contract (roll-over)
	Better than expected figures for both unemployment and industrial production in Germany
March 6	DTB - expiration of March contract (roll-over)
	Announcement of high German inflation
March 12	DTB - rumours on interest tax for foreign investors, denied by the German Finance minister in the afternoon
March 16	Bundesbank invites banks to tender for an issue of medium term treasury notes on March 24
March 18	Rumours that the German prime minister will attend tommorow's Bundesbank meeting make traders expect interest cuts
March 19	Meeting Bundesbank committee - no interest cut
March 20	DMark devalues versus US dollar - market loss
March 19-20	Futures Industry Association Meeting announces DTB-Bund listing at CBOT
March 22	Chicago Board of Options Trade and DTB sign agreement to cooperate on introduction in Bund futures trading in Chicago
March 23	Interest cut rumours from Bundesbank sources
March 24	LIFFE opens strong, collapses, stabilizes
March 26	Deutsche Bank announces: inflation peak reached
March 30	German Finance department reports on a regain of trust of foreign investors in the German capital market
March 31	Inflation in Bayern up to 5% in line with expectation
April 1	Bundesbank complains on wage-price spiral
	UK investors careful because of Labour's lead in the polls
April 2	DTB traders slightly disappointed by Bundesbank 1991 profit
April 3	DTB 'abandoned' due to weekend regional elections
April 7	Bund reacted to false rumour about pay settlement in public sector
April 9	Elections in Britain
	Annual report Bundesbank
April 10	Conservatives win elections in Britain. Relieved reaction in UK market

A first analysis of the data reveals that this Bund futures market is liquid in the sense of a high turnover. LIFFE reports on about 2.5 transactions each minute with 22.5 contracts per trade, while DTB has 1.6 transactions each minute with 23.3 contracts per trade. Hence, LIFFE accounts for approximately 1.6 times as many observations as DTB. If the APT hours are excluded from the sample, LIFFE's number of contracts per trade still exceeds that of DTB.

3. Methodology

A financial asset listed at several markets simultaneously should exhibit similar returns series for arbitrage reasons. The high quality of information technology and the possibility of rapid international capital flows contribute to this phenomenon by allowing arbitrageurs to trade within a few minutes at both exchanges. Possible spillovers at the return level will therefore occur either instantaneously or within a very short period. We also expect this to be the case for the level of volatility. When new and relevant information becomes available in one market, it is possible that this can be noticed first at the volatility level in that market and only a few moments later in the other market(s).

In this paper we seek to investigate possible intertemporal spillovers at the volatility level for the Bund futures. This implies that we can investigate whether more relevant information becomes available in which of the two markets and whether traders in one market are reacting to changes in the other market.

The Bund future is a highly liquid contract. For example, for 5-minute intervals it is possible to calculate the sample standard deviation from the returns or the prices. For 1-minute intervals, however, this is virtually impossible. We therefore need other measures in order to study the volatility of the prices or returns within the one minute interval. Another specific aspect of the Bund future is that the absolute difference between two consecutive transaction prices is often equal to zero, one or two percentage points and only a few times larger. Thus we have only a few levels of possible returns, while we have many levels of prices. We therefore follow the approach of, e.g., Webb and Smith (1994) who use the sample variance of prices rather than the sample variance of returns. Webb and Smith consider the effect of market opening and closing on the volatility of Eurodollar futures prices. For that contract virtually all changes in the prices are also the minimum move of one tick. For very short intervals like one minute intervals they use an alternative measure of volatility, i.e. the number of different prices during an interval. The main advantage of this measure, as compared to the standard deviation, is that it can be applied to shorter intervals. The disadvantage is, of course, the loss of information on the size of the price. There is no minimum number of prices required in an interval. An advantage of the first measure, which is the sample volatility of prices, is that one uses all available information in contrast to measures which only use the interval-returns. In sum, we use two different measures for volatility. The first is the sample standard deviation of prices in 5-minute intervals. The second is the number of price changes in 1-minute intervals.

In this paper, we consider volatility spillovers for the Bund futures at the 1- and 5-minute intervals. We define the volatility over the 5-minute interval t of day d or $V_{d,t}$ as the square root of the sum of the squared deviations from the average price in the interval. We also include the last price of the previous interval, since this could be seen as the best available price at the beginning of the interval. An expression for $V^M_{d,t}$ (M stands for the market, LIFFE or DTB) is

$$V^M_{d,t} = \left[\frac{(P_{d,t} - P^{N_{d,t-1}}_{d,t-1})^2 + \sum_{i=1}^{N_{d,t}} (P_{d,t} - P^i_{d,t})^2}{N_{d,t} + 1} \right]^{\frac{1}{2}}, \tag{1}$$

where $P^i_{d,t}$ is the i[th] price in interval t of day d in either of the two markets, $N_{d,t}$ is the number of prices for interval t of day d and $P_{d,t}$ is the arithmetic average of all prices in interval t and the last price in interval t-1 of day d. The volatility for 1-minute intervals is measured by the number of different prices, to be denoted as $K^M_{d,\tau}$, where τ is the time index for 1-minute intervals.

We use these volatility measures for two purposes. First, we will investigate spillovers from one market to the other market. Second, we will look at the daily pattern of the volatility and we will investigate whether proxy variables of information like volume and time-between-trades exhibit the same daily pattern as the volatility and whether they can be seen as explanatory variables for the volatility. For the second purpose we use the average time series of all available, i.e. 30, trading days since we are interested in the overall structure.

The major advantage of the Bund futures is that they are only traded in two markets at approximately the same trading hours. For the common trading hours of London and Frankfurt this market can be considered as a closed system, which is not influenced by external factors. This has the advantage that we can rely on the bivariate causality testing approach in Pierce and Haugh (1977). With causality here we mean causality in the sense of Granger (1969): A variable X causes another variable Y, with respect to a given information set (including the past values of X and Y), if present Y can be better predicted when using past values of X than by not doing so, all other information contained in the past being used in either case. In the concept of Pierce and Haugh (1977) there are basically three binary outcomes (not necessarily excluding each other), i.e. 'x causes y', 'y causes x', and 'instantaneous causality exists'. One defines 'feedback' as the case where x causes y and y causes x. Since we only have two relevant time series involved here, we do not face the problems about identifiability often encountered in multiple time series modelling.

To avoid spurious correlations between the original series due to 'domestic' characteristics, e.g. the daily U-shape pattern, the original series need to be filtered,

$$u_t = F(B)\ x_t\ , \quad v_t = G(B)\ y_t\ , \tag{2}$$

where the *F(B)* and *G(B)* are polynomial functions of the backward shift operator B, and u_t and v_t are the residual series, components of x_t and y_t that cannot be predicted from their own pasts. The x_t reflects $V_{d,t}^{LIFFE}$ in the case of 5-minute intervals and $K_{d,\tau}^{LIFFE}$ in the case of 1-minute intervals, and y_t reflects $V_{d,t}^{DTB}$ and $K_{d,\tau}^{DTB}$ in the 5- and 1-minute intervals, respectively.

Pierce and Haugh show that the residuals u_t and v_t are subject to a causality preserving transformation: the linear nature of the transformation insures that u and v are causally related in the same way as x and y. Furthermore, they show that the cross-correlations , $\rho_{u,v}$(k) (the cross-correlation between u_t and v_{t+k}), between the whitened or filtered series, can be used to characterize any causality event. For example, y does not cause x if and only if $\rho_{u,v}(k)=0,\ k<0$. All we need is that u_t and v_t are each univariate white noise series. If so, there exists instantaneous causality if and only if $\rho_{u,v}(0)\neq 0$. The causality direction however cannot be detected in this case. Whether there is instantaneous causality from X to Y, from Y to X, or both cannot be ascertained from the data.

Our first concern is now to get the whitened or filtered series from the original series as in (2). For this purpose we use the Box Jenkins (1970) approach to estimate the appropriate filters from the sample series. Thus we get

$$\hat{u}_t = \hat{F}(B)\ x_t\ , \quad \hat{v}_t = \hat{G}(B)\ y_t\ , \tag{3}$$

where the estimated filters can be found via estimating autoregressive moving average (ARMA) processes. In our case we will consider AR(10) filters, see section 4.

Causality analysis is carried out using the sample residual cross-correlations

$$\hat{r}_k = r_{\hat{u}\hat{v}}(k) = \frac{\sum \hat{u}_{t-k}\,\hat{v}_t}{\sqrt{\sum \hat{u}_t^2 \sum \hat{v}_t^2}} \quad , \tag{4}$$

where k is an integer. Under the assumption of series independence it is shown in Pierce and Haugh (1977) that any vector of the correlations like (4) is asymptotically normally distributed:

$$\sqrt{n}\,\hat{r} \sim N(0, I) \quad , \quad \hat{r} = (\hat{r}_{k_1}, \ldots, \hat{r}_{k_m}) \quad , \tag{5}$$

where k_i are integers, and hence that

$$n\hat{r}'\hat{r} = n\sum_{i=1}^{m} \hat{r}_{k_i}^2 \tag{6}$$

is $\chi^2(m)$ distributed under the null hypothesis of independence.

To summarize, we investigate spillovers between the two volatility time series of the two markets in terms of Granger causality applying the following two steps: (i) We prewhiten the original volatility series via (3) and (ii) we calculate cross-correlations between the prewhithened series using (4).

Our second goal in this paper is to investigate the daily pattern of volatility. For this purpose we analyse the sample volatility in each 5-minute interval, averaged over all 30 trading days. Along the lines of the findings of Webb and Smith (1994) for the Eurodollar futures, we expect to find a U-shape in the average volatility series, i.e. high volatility in the opening minutes, decreasing until lunch time and increasing after lunch. To investigate this shape we split up every day into three periods and test whether volatility differs significantly across these periods by means of variance analysis. Following Lockwood and Linn (1990) we use the test statistic,

$$F = \frac{\frac{1}{J-1}\sum_{j=1}^{J} n_j\,(V_{.j}-V_{..})^2}{\frac{1}{N-J}\sum_{j=1}^{J}\sum_{i=1}^{n_j}(V_{ij}-V_{.j})^2} \tag{7}$$

where V_{ij} denotes the ith observation of the volatility in intra-day period j, $V_{.j}$ is the average volatility over the n_j observations in period j, and $V_{..}$ is the overall mean. Under the null hypothesis of a constant volatility level this F statistic is approximately F distributed with 2 and N-2 degrees of freedom. Note that this statistic is independent of volatility clustering for successive intervals, since we average volatility over all available trading days. When F exceeds the relevant critical value and when the V_{ij} pattern resembles a U-shape, we reject the null hypothesis that the volatility level is constant during the day in favor of the U-shape pattern. We will also look at the daily patterns of volume, time-between-trades and bid-ask spreads. In the next section we will see that these proxy variables of information either exhibit a similar U-shape or exactly the opposite pattern.

To investigate whether the U-pattern for volatility can be totally explained by proxy variables, we will use a simple linear regression to correct the sample volatility for the effects of volume, time-between-trades and the bid-ask spread,

$$\Phi(B)\,V_t = c + \alpha * VOL_t + \beta * (1/TBT_t) + \gamma * BAS_t + \epsilon_t \qquad (8)$$

where $\Phi(B)$reflects an AR(10) filter in our application below, V_t is the 5-minute intervals sample volatility averaged with respect to all the trading days in the sample, VOL is the same for the volume within the intervals, TBT for the time-between-trades and BAS for the bid-ask spread. Since the empirical pattern of TBT mirrors that of a U-shape, we consider the inverse of TBT in equation (8). We could also try other informations, but we do not expect this to matter much. Estimating (8) we can test for significant effects of the information proxy variables, and we can test whether these variables can explain the U-shape pattern. The latter can be done by calculating the F-test in equation (7) using the residual series of (8) correcting for the dynamics in V_t:

$$V_t^* = V_t - \frac{1}{1-\hat{\phi}_1-\ldots-\hat{\phi}_{10}}[\hat{c} + \hat{\alpha}*VOL_t + \hat{\beta}*1/TBT_t + \hat{\gamma}*BAS_t] \qquad (9)$$

Finally, to investigate whether LIFFE and DTB have the same specific pattern, we use the F-test on the difference between the volatility series of LIFFE and DTB.

4. Results

Clustering of volatility of an asset is a phenomenon often encountered in empirical financial studies. Periods of high volatility follow periods of low volatility. In Table 1 we present the first order autocorrelations of the daily 5-minute volatility series, $V^{M}_{d,t}$, and the 1-minute volatility series, $K^{M}_{d,\tau}$, to check for potential positive serial correlation.

We find for DTB that 26 out of 30 autocorrelations are significantly positive, for LIFFE this is 19 out of 30. This implies that some autocorrelation structure has to be removed in order to estimate cross-effects via the correlation measure in (4). For convenience we choose to estimate an AR(10) model for all volatility series to remove the dynamic structure of the individual series. This includes the individual U-shape pattern for both markets. Although we could have applied the familiar Box-Jenkins method to specify specific ARMA models for each of the series, we assume that an AR(10) is sufficient to whiten the series. While setting the lag length at 10, we consider the inefficiency of this probably overparameterised model to be less important than spurious correlations, $\hat{r}_k$, due to too restrictive models. The residuals from these AR(10) models constitute prewhitened series for both exchanges, for which we compute cross-correlations. We only use the volatility of the series from 7:30 until the close of LIFFE-OOC, 16:15, because we want to avoid a potential influence of a change of the trading system on spillovers. A positive value of the cross-correlation $\rho(V_d^{DTB}, V_d^{LIFFE})(1)$, between the current volatility of LIFFE and the volatility of DTB lagged five minutes, is interpreted as a lead of DTB on LIFFE. A positive value of the contemporaneous cross-correlation of DTB and LIFFE, $\rho(V_d^{DTB}, V_d^{LIFFE})(0)$, implies simultaneous movements of volatility. To save space, we limit ourselves to an analysis of cross-correlations at one period lagged only.

The results of the computation of these cross-correlations are presented in Table 2. Out of 90 observed cross-correlations 74 are positive and none of the negative ones is significant at the 5% level. Simultaneous cross-correlation is more often significant at the 5% level than intertemporal cross-correlations. Simultaneous cross-correlation is significant for 26 of the 30 trading days. Intertemporal cross-correlations are typically not significant, except for 2 cross-correlations indicating a lead of DTB on LIFFE and 3 indicating a lead of LIFFE on DTB. However, this small number of significant results may indicate that a 5-minute interval is too large to detect potential spillovers of volatility from LIFFE to DTB and vice versa.

TABLE 1: CLUSTERING IN THE UNIVARIATE VOLATILITY SERIES

FIRST ORDER AUTO-CORRELATION IN THE VOLATILITY SERIES $V^M_{d,t}$ AND $K^M_{d,\tau}$.
$V^M_{d,t}$ IS STANDARD DEVIATION OF BUND FUTURES PRICES AT EXCHANGE M IN 5-MINUTE INTERVAL t OF DAY d.
$K^M_{d,\tau}$ IS NUMBER OF DIFFERENT BUND FUTURES PRICES AT EXCHANGE M IN 1-MINUTE INTERVAL τ OF DAY d.

	AUTO-CORRELATION					AUTO-CORRELATION			
	$V^M_{d,t}$		$K^M_{D,\tau}$			$V^M_{d,t}$		$K^M_{d,\tau}$	
DATE	DTB	LIFFE	DTB	LIFFE	DATE	DTB	LIFFE	DTB	LIFFE
MARCH 2	0.24*	0.34*	0.15*	0.16*	MARCH 23	0.13	0.15	0.33*	0.19*
3	0.13	0.16	-0.03	0.22*	24	0.11	0.18	0.43*	0.39*
4	0.32*	0.26*	0.24*	0.36*	25	0.42*	0.29*	0.23*	0.44*
5	0.23*	0.18	0.38*	0.41*	26	0.20*	0.15	0.23*	0.32*
6	0.37*	0.18	0.43*	0.41*	27	0.20*	0.29*	0.21*	0.29*
9	0.23*	0.15	0.05	0.26*	30	0.20*	0.27*	0.32*	0.38*
10	0.41*	0.34*	0.28*	0.24*	31	0.20*	0.04	0.29*	0.26*
11	0.36*	0.27*	0.17*	0.29*	APRIL 1	0.17	0.23*	0.22*	0.23*
12	0.22*	0.22*	0.29*	0.34*	2	0.27*	0.07	0.25*	0.28*
13	0.30*	0.38*	0.45*	0.42*	3	0.27*	0.32*	0.13*	0.40*
16	0.27*	0.21*	0.08*	0.28*	6	0.30*	0.24*	0.57*	0.36*
17	0.45*	0.54*	0.20*	0.41*	7	0.53*	0.43*	0.28*	0.29*
18	0.38*	0.31*	0.45*	0.34*	8	0.28*	0.19*	0.24*	0.38*
19	0.22*	0.19	0.21*	0.35*	9	0.22*	0.25*	0.31*	0.44*
20	0.27*	0.19	0.40*	0.33*	10	0.41*	0.41*	0.44*	0.14*
NUMBER OF OBSERVATIONS[A]	94	94	510	510		94	94	510	510
STANDARD ERROR[B]	0.10	0.10	0.04	0.04		0.10	0.10	0.04	0.04
MEAN OVER ALL TRADING DAYS						0.28	0.25	0.27	0.32

* Significance at a 5% level.
[A] The number of effective observations in our regressions.
[B] The standard error of the auto-correlation in a series of N obervations is calculated as $1/\sqrt{N}$.

TABLE 2: VOLATILITY SPILLOVERS AT THE 5-MINUTE LEVEL

THE STANDARD DEVIATION OF BUND FUTURES PRICES IN A 5-MINUTE INTERVAL IS USED TO CONSTRUCT INTRADAY VOLATILITY SERIES. AUTOCORRELATION IN THESE SERIES IS REMOVED WITH AN AR(10) MODEL. THE RESIDUALS ARE USED TO ESTIMATE (INTERTEMPORAL) CROSS-CORRELATION BETWEEN VOLATILITY OF THE BUND-FUTURES ON LIFFE AND DTB.

	CROSS-CORRELATION				CROSS-CORRELATION		
DATE	DTB LEADS	SIM	LIFFE LEADS	**DATE**	DTB LEADS	SIM	LIFFE LEADS
MARCH 2	0.16	0.13	0.20*	**MARCH 23**	0.14	0.72*	0.04
3	0.05	0.12	0.28*	**24**	-0.08	0.74*	-0.01
4	0.18	0.47*	0.11	**25**	0.17	0.60*	-0.08
5	0.08	0.64*	0.10	**26**	-0.04	0.73*	0.01
6	0.12	0.10*	0.15	**27**	0.00	0.55*	0.11
9	0.06	0.18	0.01	**30**	-0.09	0.75*	0.24*
10	-0.02	0.49*	0.06	**31**	0.14	0.66*	-0.11
11	-0.01	0.40*	0.15	**APRIL 1**	-0.01	0.66*	0.06
12	0.14	0.34*	0.18	**2**	0.17	0.11	-0.02
13	0.15	0.61*	0.07	**3**	0.13	0.38*	0.13
16	0.04	0.34*	0.11	**6**	0.00	0.72*	-0.05
17	0.13	0.56*	0.14	**7**	0.21*	0.55*	-0.01
18	-0.07	0.62*	0.14	**8**	0.14	0.61*	-0.01
19	0.21*	0.62*	0.10	**9**	-0.01	0.81*	0.05
20	0.06	0.74*	0.05	**10**	-0.02	0.76*	0.14
NUMBER OF OBSERVATIONS[A]	94	94	94		94	94	94
STANDARD ERROR[B]	0.10	0.10	0.10		0.10	0.10	0.10
MEAN OVER ALL TRADING DAYS					0.07	0.52	0.08

* Significant at a 5% level.

[A] The number of effective observations in our regressions.

[B] The standard error of the cross-correlation between to series of length N is calculated as $1/\sqrt{N}$.

High liquidity of the Bund futures on both exchanges enables us to study spillovers at the 1-minute level. As stated before, the standard deviation measure is not useful now, and therefore we apply the number of observed prices, $K^M_{d,\tau}$. The first order autocorrelation of the $K^M_{d,\tau}$ series is computed to investigate clustering. The results are also presented in Table 1. It can be seen that for DTB 28 out of 30 and for LIFFE all trading days show significant positive autocorrelations. Again, consider an AR(10) model to prewhiten the volatility series. These prewhitened series are used to compute the cross-correlations $\rho(K^{DTB}_d, K^{LIFFE}_d)(1)$, $\rho(K^{DTB}_d, K^{LIFFE}_d)(1)$ and $\rho(K^{DTB}_d, K^{LIFFE}_d)(0)$.

The results are reported in Table 3. From this table we can observe that only 2 out of 90 cross-correlations are (insignificantly) negative. Simultaneous correlation again is very often significantly positive, in 28 out of 30 trading days. If we compare the mean simultaneous cross-correlation over the trading days for the 5-minute level and the 1-minute level, we find that they both are five times larger than their standard error. The differences between the 5- and 1-minute analysis emerge when analysing leads and lags. We find significant positive cross-correlations indicating a lead of DTB for 17 out of 30 days and significant correlations indicating a lead of LIFFE for 20 out of 30 days for LIFFE. Hence, volatility spillovers seem to occur more often at the 1-minute level than at the 5-minute level.

A closer look at the 1-minute volatility spillovers indicates that 11 out of 30 trading days have a significant lead of LIFFE on DTB and vice versa. An interpretation is that important news has stirred both markets of Bund futures. Different interpretations of the same news in London and Frankfurt may make volatility spill over from London to Frankfurt and back within one trading day. Furthermore we find a 'pure' lead of DTB, occurring 6 days, and a 'pure' lead of LIFFE, occurring 9 days. A 'pure' lead of DTB can be a result of news that originates from Germany and which affects the UK throughout the day. Such an interpretation can be investigated by combining Table 3 with the lead and lags and Figure 2 with the financial news. In the first week, except for March 5, simultaneity is weak compared to the rest of the period. LIFFE leads after March 4, the day before the expiration of the March contract on LIFFE. In the next period until March 30, LIFFE leads most of the days. When the lead of DTB is significant the cross-correlation value for LIFFE is high too, except for March 10 and March 25. The last period of our sample shows the opposite.

TABLE 3: VOLATILITY SPILLOVERS AT THE 1-MINUTE LEVEL

THE NUMBER OF DIFFERENT BUND FUTURES PRICES IN A 1-MINUTE INTERVAL IS USED TO CONSTRUCT INTRADAY VOLATILITY SERIES. AUTOCORRELATION IN THESE SERIES IS REMOVED WITH AN AR(10) MODEL. THE RESIDUALS ARE USED TO ESTIMATE (INTERTEMPORAL) CROSS-CORRELATION BETWEEN VOLATILITY OF THE BUND-FUTURES ON LIFFE AND DTB.

	CROSS-CORRELATION				CROSS-CORRELATION		
DATE	DTB LEADS	SIM	LIFFE LEADS	DATE	DTB LEADS	SIM	LIFFE LEADS
MARCH 2	0.08*	0.10*	0.05	**MARCH 23**	0.10*	0.18*	0.11*
3	0.07	0.09*	0.01	**24**	0.15*	0.13*	0.17*
4	0.08*	0.04	0.13*	**25**	0.16*	0.32*	0.08*
5	0.06	0.21*	0.12*	**26**	0.04	0.26*	0.12*
6	0.03	-0.01	0.10*	**27**	0.06	0.18*	0.15*
9	0.02	0.16*	0.05	**30**	0.17*	0.38*	0.06
10	0.16*	0.19*	0.10*	**31**	0.19*	0.33*	0.04
11	-0.02	0.16*	0.03	**APRIL 1**	0.09*	0.29*	0.04
12	0.09*	0.29*	0.08*	**2**	0.13*	0.23*	0.16*
13	0.10*	0.23*	0.08*	**3**	0.06	0.25*	0.12*
16	0.03	0.10*	0.03	**6**	0.11*	0.25*	0.07
17	0.19*	0.22*	0.14*	**7**	0.05	0.29*	0.08*
18	0.05	0.17*	0.11*	**8**	0.10*	0.25*	0.06
19	0.00	0.23*	0.14*	**9**	0.20*	0.23*	0.12*
20	-0.01	0.27*	0.09*	**10**	0.14*	0.19*	0.15*
NUMBER OF OBSERVATIONS[A]	510	510	510		510	510	510
STANDARD ERROR[B]	0.04	0.04	0.04		0.04	0.04	0.04
MEAN OVER ALL TRADING DAYS					0.09	0.21	0.09

* Significant at a 5% level.

[A] Number of effective observations in our regressions.

[B] The standard error of the cross-correlation between two series of length N is calculated as $1/\sqrt{N}$.

With the exception of April 3, DTB seems to lead until April 9 and 10, when simultaneity takes over. Although not very clear this could reflect a few facts mentioned in Figure 2. In the first few days of our sample the June contract, which is investigated here, is not the main contract. Only after March 6 this contract has fully taken over the market from the March contract. The fact that the June contract is not yet the most important contract could cause less simultaneity which is not found elsewhere in the sample period. The observation that LIFFE seems to lead could be explained by the large volume compared to DTB. In the period from March 30 until April 9 prices at British capital markets fell sharply. The fear of the Labour-party winning the elections caused the stock and bond traders in London reluctant to trade. It might be this effect that gave DTB the opportunity to take a lead. In line with the reasoning above we expect the situation before March 30 to re-establish after April 9. The simultaneity of April 9 and 10 may be the first sign of that phenomenon.

We now turn to an investigation of the structural intraday patterns. For each 5-minute interval of trade on either exchange we compute the mean over all trading days of volatility, measured by $V^M_{d,t}$, see (1). The mean volatility series for LIFFE and DTB are depicted in Figures 3 and 4, respectively.

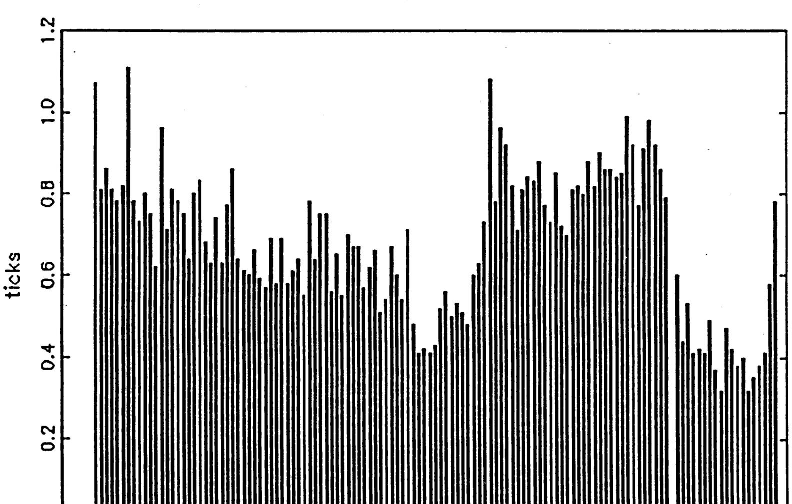


Figure 3: Average price volatility in 5-minute intervals - Bund future on LIFFE for the period March 2 until April 10, 1992. Price volatility is measured by the standard deviation of price.

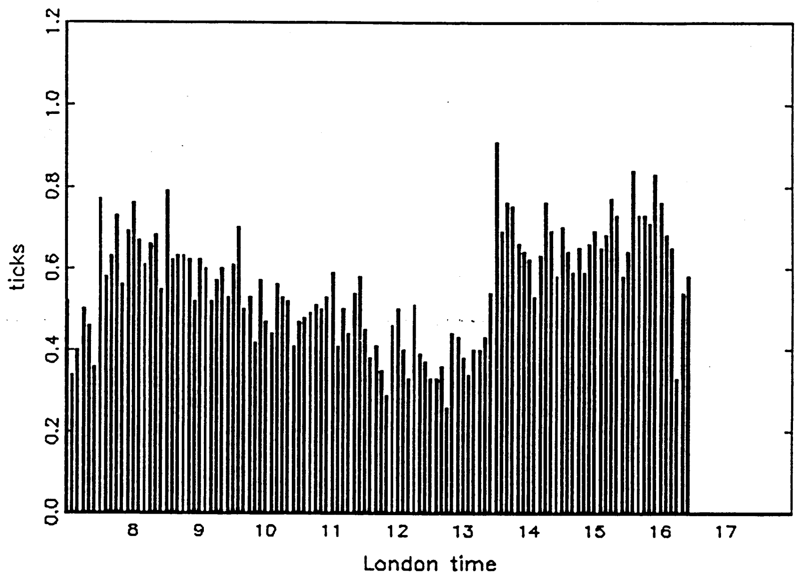


Figure 4: Average price volatility in 5-minute intervals - Bund future on DTB for the period March 2 until April 10, 1992. Price volatility is measured by the standard deviation of price.

Notice that LIFFE-OOC is more volatile (mean volatility of 0.72) than DTB (mean volatility of 0.56) and that LIFFE-APT is the least volatile (mean volatility of 0.45). This seems to confirm that LIFFE-APT serves as a system merely to offset positions at the end of the day. Given this, we will not consider LIFFE-APT in subsequent analysis and concentrate on LIFFE-OOC and DTB only. Second, notice that the mean standard deviations are small and show the small price changes in the Bund futures trade. Furthermore, a U-shape can be recognized in both series. Volatility decreases until early noon and rises thereafter to stay at a high level until closing time. The peak of 13:30 hours can be seen as a turning point. This point marks the end of the 'fixing' period. Hence, the final price of the Bund causes volatility to rise on the Bund futures exchange. The volatility jump at 7:30 hours reflects a delayed start of DTB. Until the opening of LIFFE, 7:30 hours, volatility is relatively low in Frankfurt. At 16:15, when LIFFE closes for 5 minutes changing to the APT system, we see a drop in the volatility of DTB. These facts combined with lower volatility, lower average volume of transactions and less transactions within a minute indicates the active role of LIFFE.

Except for the volatility at the 5- and 1-minute level we also calculate the volume, the average time-between-trades and, for LIFFE, the average bid-ask spread for each 5-minute interval. Volume is computed as the total number of contracts traded in a 5-minute interval, time-between-trades as the average time between transactions and the bid-ask spread as the difference between the last bid quote and the last ask quote in an interval. Because these quotes need not emerge at the same time and because there can be several quotes in between that were directly hit and recorded as transaction, the bid-ask spread might be zero or negative. In those cases we decide not to include these quotes. The average of all three variables over the 30 trading days is computed and depicted in Figures 5 through 9.

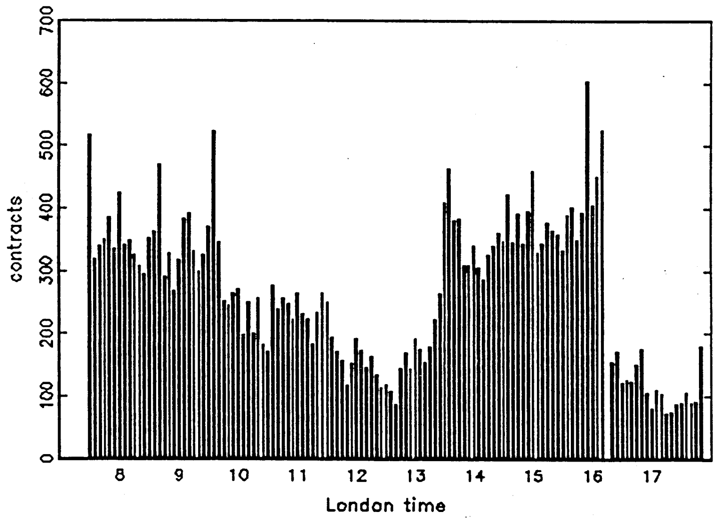


Figure 5: Average number of contracts that are traded in 5-minute intervals - Bund future on LIFFE for the period March 2 until April 10, 1992.

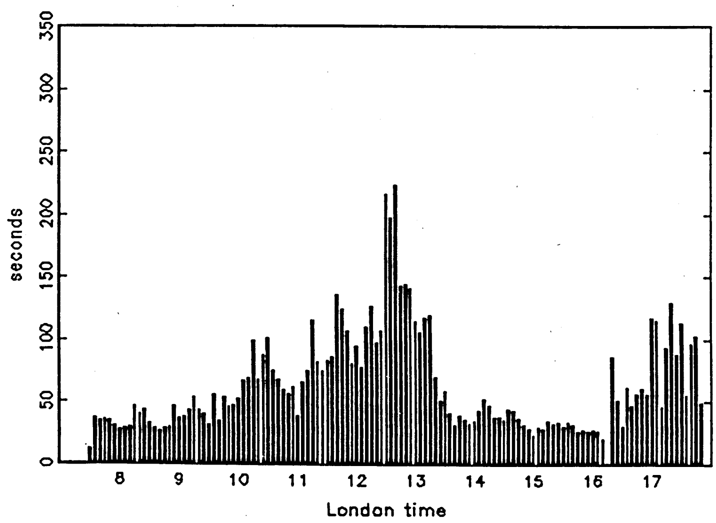


Figure 6: Average time-between-trades in 5-minute intervals - Bund future on LIFFE for the period March 2 until April 10, 1992.

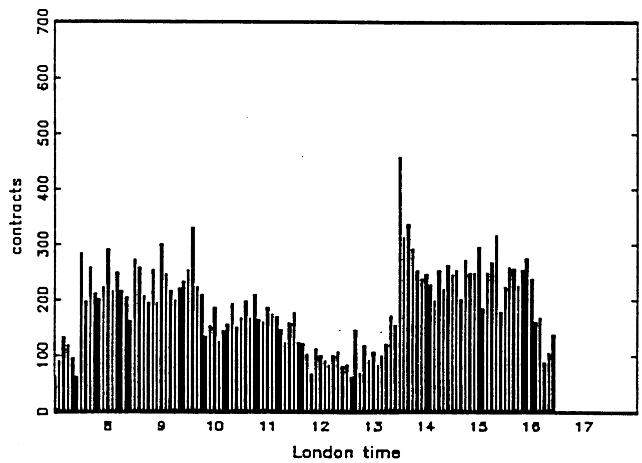


Figure 7: Average number of contracts that are traded in 5-minute intervals - Bund future on DTB for the period March 2 until April 10, 1992.

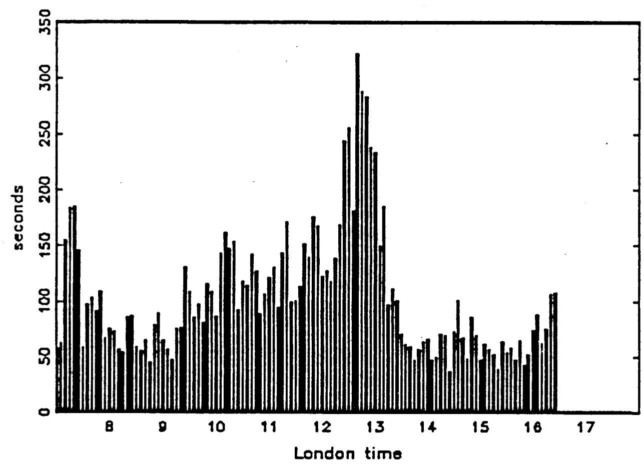


Figure 8: Average time-between-trades in 5-minute intervals - Bund future on DTB for the period March 2 until April 10, 1992.

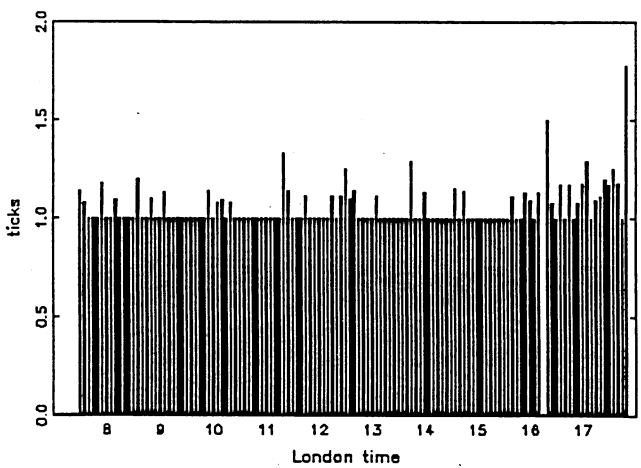


Figure 9: Average bid-ask spread for each 5-minute interval - Bund future on LIFFE for the period March 2 until April 10, 1992. Zero or negative spreads have been withdrawn from the sample.

At first sight, we observe a U-shape in most of the displayed series. To check if variables like volume, time-between-trades and bid-ask spread can explain the U-shape pattern in the volatility series, we perform some regressions, see (8). Volatility at the 5-minute interval level is the dependent variable in these regressions. For LIFFE we have volume, time-between-trades and bid-ask spread as explanatory variables. For DTB, bid-ask-quotes are however not available.

The results are presented in Table 4. From the t-ratios reported in this table, we conclude that the bid-ask spread does not seem to explain current volatility. The volume and the inverse of time-between-trades, however, *individually* influence volatility. These variables explain 64 up to 81 percent of the volatility variance, although explanatory power of time-between-trades additional to volume is poor. For DTB as well as for LIFFE, the time-between-trades is insignificant and there is no increase in R^2 in this case. High correlation between volume and the inverse of time-between-trades is due to the fact that these reflect the same variable if the volume per trade is constant. To summarise, we conclude from the regression results that volatility is best explained by volume.

To test for the apparent U-shape we consider the following procedure. We find a U-shape in a certain time series if the F-statistic in equation (7) rejects the null hypothesis of constant mean, and if we find large means at the beginning and end of the day compared to a lower mean around noon. Our results are presented in Table 5. The null hypotheses of constant volatility is rejected at the 1% level for both exchanges. To investigate if the U-shape on both exchanges can be traced back to a common feature, we investigate the series in which the volatility of LIFFE is subtracted from the volatility of DTB. The result is given in the eighth row of Table 5. We find that constant volatility cannot be rejected at the 10% level, indicating that DTB and LIFFE have similar U-shapes.

Other proxy variables of information are volume, time-between-trades and bid-ask spreads. The volume for LIFFE and DTB seems to have a U-shape similar to the pattern of the volatility series, see Figures 5 and 7. Our U-shape test seems to confirm this, as can be seen from Table 5, rows two and six. The time-between-trades pictures show the inverse pattern. After all, this variable is the inverse of the volume variable if each transaction consists of a fixed number of contracts. In our regressions we use the inverse of time-between-trades, therefore the U-shape test is performed to the inverse instead of the time-between-trades itself.

TABLE 4: VOLATILITY EXPLAINED BY VOLUME, BID-ASK SPREAD AND THE INVERSE OF TIME-BETWEEN-TRADES AT THE 5-MINUTE LEVEL

		COEFFICIENTS				
	RESTRICTION	CONSTANT	VOL	1/TBT	BAS	R^2
LIFFE	$\beta=\gamma=0$	0.28 (4.50)	0.00085 (5.96)	-	-	0.72
	$\alpha=\gamma=0$	0.31 (3.45)	-	6.21 (3.18)	-	0.64
	$\alpha=\beta=0$	0.094 (0.52)	-	-	0.0071 (0.044)	0.60
	$\gamma=0$	0.30 (3.77)	0.00081 (4.76)	0.87 (0.42)	-	0.72
	-	0.41 (2.42)	0.00083 (4.80)	0.80 (0.38)	-0.101 (-0.74)	0.72
DTB	$\beta=0$	0.078 (2.26)	0.0012 (8.66)	-		0.81
	$\alpha=0$	0.12 (2.31)	-	7.12 (2.36)		0.66
	-	0.079 (2.01)	0.0012 (8.02)	0.15 (0.064)		0.81

THE ESTIMATED EQUATION IS $\Phi(B)V_t = c + \alpha^*VOL_t + \beta^*(1/TBT_t) + \gamma^*BAS_t + \varepsilon_t$
WHERE V=VOLATILITY, VOL=VOLUME, TBT=TIME-BETWEEN-TRADES AND BAS=BID-ASK SPREAD.
$\Phi(B)$ REFLECTS AN AR(10) FILTER, THE PARAMETERS OF WHICH ARE NOT GIVEN HERE.
TOTAL SAMPLE PERIOD: 7:30-16:15 I.E. 105 OBSERVATIONS; BECAUSE OF THE AR(10) FILTER THERE ARE 95 EFFECTIVE OBSERVATIONS IN OUR REGRESSIONS.
t-VALUES BETWEEN BRACKETS

TABLE 5: VARIANCE ANALYSIS OF INTRADAY VOLATILITY, RELATED SERIES AND RESIDUAL SERIES OF EQUATION (9)

		MEANS OVER TIME			F
		MORNING	FIXING	AFTER-NOON	
LIFFE	STDV	0.72 (0.13)	0.55 (0.09)	0.85 (0.08)	49.41*
	VOLUME	304 (79)	164 (43)	381 (65)	70.22*
	1/TBT	0.024 (0.02)	0.0094 (0.0007)	0.030 (0.001)	39.07*
	BAS	1.04 (0.07)	1.04 (0.07)	1.04 (0.07)	0.02
DTB	STDV	0.57 (0.09)	0.40 (0.07)	0.70 (0.08)	88.24*
	VOLUME	204 (47)	108 (30)	252 (55)	66.94*
	1/TBT	0.012 (0.0006)	0.0064 (0.0005)	0.017 (0.0007)	62.40*
LIFFE-DTB	STDV	0.15 (0.07)	0.16 (0.07)	0.15 (0.06)	0.11
RESIDUAL SERIES OF TABLE 4 CORRECTED FOR DYNAMICS IN V_t					
LIFFE	B=Γ=0	-0.022 (0.08)	-0.011 (0.06)	0.033 (0.09)	4.46
	A=Γ=0	-0.019 (0.08)	-0.036 (0.08)	0.047 (0.11)	7.25*
	A=B=0	-0.030 (0.10)	-0.16 (0.10)	0.13 (0.08)	73.66*
	Γ=0	-0.022 (0.08)	-0.011 (0.06)	0.033 (0.09)	4.46
	-	-0.022 (0.08)	-0.011 (0.06)	0.033 (0.09)	4.52
DTB	B=0	-0.022 (0.08)	0.017 (0.06)	0.0063 (0.10)	2.05
	A=0	0.0032 (0.08)	-0.059 (0.06)	0.033 (0.11)	7.51*
	-	-0.022 (0.08)	0.017 (0.06)	0.0063 (0.10)	2.00

STDV DENOTES THE SERIES OF STANDARD DEVIATIONS OF PRICES, VOLUME THE TOTAL NUMBER OF TRADED CONTRACTS, TBT THE AVERAGE TIME-BETWEEN-TRADES (IN SECONDS) AND BAS DENOTES THE AVERAGE BID-ASK SPREAD. ALL MEASURES ARE COMPUTED FOR 5-MINUTE INTERVALS. MORNING 7:30-11:30 (48 OBSERVATIONS, 38 EFFECTIVE IN REGRESSIONS OF TABLE 4), FIXING 11:30-13:30 (24 OBSERVATIONS) AND AFTERNOON 13:30-16:15 (33 OBSERVATIONS).
BID- AND ASK-QUOTES ARE NOT AVAILABLE FOR DTB.
FOR EACH SERIES THE MEAN IN EACH PERIOD IS GIVEN ALONG WITH THE STANDARD DEVIATION IN BRACKETS.
F DENOTES THE VALUE OF THE F-TEST IN EQUATION (7) WITH 2 AND 103 (93 IN THE SECOND PART) DEGREES OF FREEDOM.
THE 1% CRITICAL VALUE IS ABOUT 4.85.
THE NULL HYPOTHESIS IS THAT THE TIME SERIES HAS A CONSTANT VARIANCE; REJECT IN FAVOUR OF A U-SHAPE WHEN THE TEST STATISTIC EXCEEDS THE CRITICAL VALUES AND THE MEAN OF THE FIXING IS LOWER THAN THE MEAN OF THE MORNING AND AFTERNOON. THESE CASES ARE INDICATED BY *.

The significant numbers in rows three and seven in Table 5 suggest that again we can reject the constant volatility null hypothesis. The bid-ask spread, however, does not show any sign of a U-shape. Table 5, row four, indicates that we cannot reject the null hypothesis of constant bid-ask spread throughout the day.

The explanatory power of the regressions in Table 4 can also be investigated using our U-shape test. If the explanatory variables and the volatility have a common U-shape feature, the residual series should not contain such a structural U-pattern. Corresponding to the results in Table 4, it can be observed from the ninth and fourteenth row in Table 5 that volume by itself is able to remove the U-shape. It is obvious that the bid-ask spread cannot be able to explain the U-shape in volatility.

A relatively high volatility at both the beginning and at the end of the day while the bid-ask spread is constant may lead to the following tentative conclusion. Liquidity traders, who move in and out the market by attempting to profit from short-term price changes, can best trade at the beginning and end of the day. These periods have the highest profit potential. Another way to asses profit-likelihood for each 5-minute interval is to evaluate for how many days a trader with perfect foresight will be able to make a profit in that interval. The best strategy for a perfectly informed trader is to buy at the lowest ask and to sell at the highest bid for each interval. If the highest bid is higher than the lowest ask, the trader can make a profit. In that case the trader outperforms the spread. Whether one should go short or long is determined by the sequence in which the highest bid and lowest ask occur in the interval.

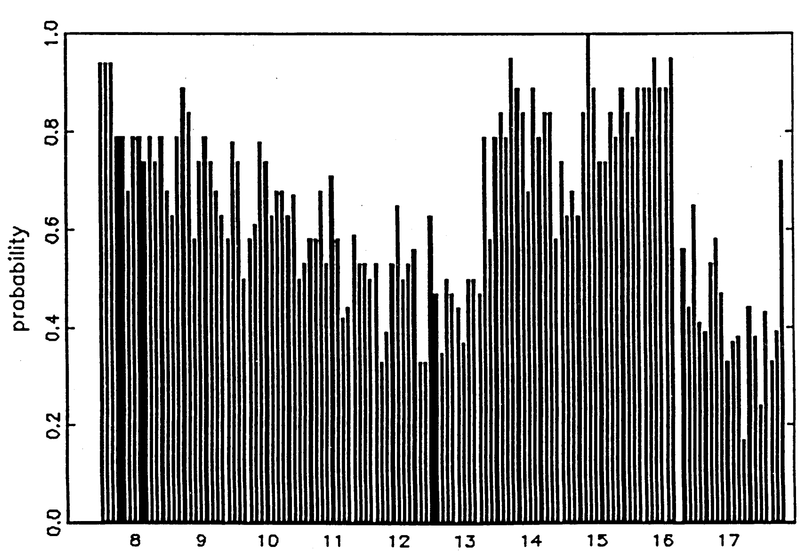


Figure 10: Probability that the highest bid exceeds the lowest ask for each 5-minute interval - Bund future on LIFFE for the period March 2 until April 10, 1992.

Figure 10 shows how often such a profit can be made by a fully informed trader in a particular interval. As expected, we detect a U-shape and therefore we conclude that trading to achieve short-term profit should be conducted at the beginning and end of trading days. Thus, a trader can overcome profit offsetting bid-ask spread costs.

5. Conclusions

This paper investigates two aspects of the intraday volatility of the Bund-future, i.e. spillovers between the two exchanges, LIFFE in London and DTB in Frankfurt, and a commonly found U-shape pattern. The investigation is carried out using data for the period of March 2 until April 10 1992. The data consist of all transaction prices, volumes and exact time to the nearest second of both exchanges, as well as the bid- and ask-quotes that were not immediately hit for LIFFE.

In 5-minute intervals about 5 to 10 contracts are traded at both LIFFE and DTB. This enables us to use standard-deviation as a measure of volatility for these intervals. The small variation in price changes -typically 1 or 2 ticks- urges us to use the standard deviation of prices instead of the standard deviation of returns. The volatility series show significant autocorrelation (clustering). Therefore we prewhiten these series using AR(10) models before we analyse causality structures. The resulting series indicate strong simultaneity at the 5-minute level and sheer absence of a significant lead of either one of the exchanges.

For 1-minute intervals it is difficult to calculate the sample standard deviation of prices because there are intervals in which only one transaction takes place. We therefore choose to use the number of different prices as a measure of volatilty at the 1-minute level. The prewhitened series still show simultaneity, but now we also find lead/lag relations. Unfortunately, there are no structural spillovers from one exchange to the other for all trading days. A potential explanation is that such relations depend on the origin of the daily news. To some extent the main news items in the investigated period are reflected in the leads and lags indeed, but there are exceptions that cannot be explained using these published news facts.

A U-shape in intraday volatility seems evident for both exchanges, when we aggregate series over all available trading days using the 5-minute series. In the morning traders are trying to establish a new price reflecting the news that has emerged since the closing of the market the previous day. Regular trade usually takes place at a lower level of volatility but at the end of the day many traders try to offset their positions, which causes increasing volatility in the markets. A reasonable partition of the day is to consider the morning until 11:30 hours, the fixing (period of trade in the underlying asset) until 13:30 hours and the afternoon until 16:30 hours apart. Volatility, volume and the inverse of time-between-trades all have a low mean over the fixing compared to the morning and afternoon. Using an F-test we are able to reject the null-hypothesis of constant mean, which validates the U-shape in the above mentioned series. Moreover, we find that these variables have this U-shape feature in common. On the other hand, the bid-ask spread (at LIFFE) shows no sign of a U-shape. It appears that liquidity traders who offset their position each 5-minute interval and know in advance which is the lowest ask and the highest bid each interval, have high profit probabilities at the beginning and end of a trading day.

References

Bollerslev, T., and I. Domowitz, 1993, Trading patterns and prices in the interbank foreign exchange market, *Journal of Finance* 48, 1421-1443.

Bollerslev, T., and M. Melvin, 1994, Bid-ask spreads and volatility in the foreign exchange market. An empirical analysis, *Journal of International Economics* 36, 355-372.

Box, G.E.P., and G.M. Jenkins, 1970, *Time series analysis forecasting and control*, Holdenday, San Fransisco, CA.

Ederington, L.H., and J.H. Lee, 1993, How markets process information: News releases and volatility, *Journal of Finance* 48, 1161-1191.

Granger, C.W.J., 1969, Investigating causal relations by econometric models and cross spectral methods, *Econometrica* 37, 424-438.

Granger, C.W.J., 1992, Forecasting stock market prices: lessons for forecasters, International *Journal of Forecasting*, 8, 3-13.

Hausman, J.A., A.W. Lo, and A.C. MacKinlay, 1992, An ordered probit analysis of transaction stock prices, *Journal of Financial Economics* 31, 319-379.

Lockwood, L.J., and S.C. Linn, 1990, An examination of stock market return volatility during overnight and intraday periods, 1964-1989, *Journal of Finance* 45, 591-601.

Pierce, D.A., and L.D. Haugh, 1977, Causality in temporal systems, characterizations and a survey, *Journal of Econometrics* 5, 265-293.

Webb, R.I., and D.G. Smith, 1994, The effect of market opening and closing on the volatility of Eurodollar futures prices, *Journal of Futures Markets* 14, 51-78.

Wood, R.A., T.H. McInish, and J.K. Ord, 1985, An investigation of transaction data for NYSE stocks, *Journal of Finance* 40, 723-741.